MINIATURE ULTRASONIC ROTARY MOTORS

Yoseph Bar-Cohen, Mike Lih
yosi@jpl.nasa.gov
JPL, California institute of Technology, Pasadena, CA

and

Nesbitt **W. Hagood**
Aeronautics **and Astronautics,**
MIT Cambridge, MA 02139

2nd Micromachining **Workshop, Anaheim, CA, September 27 and 28, 1995,**
Sponsored by the Southern California Chapter of the American Vacuum Society

ULTRASONIC MOTORS - BACKGROUND

<u>**Operation principle**</u>: Traveling plate/surface waves cause surface particles to move in a circular motion. This motion is used to propel the rotor.

- ♦ The motion is the result of accumulated minute displacements.
- ♦ Piezoelectric discs, i.e. stator, are use to excite the wave.
- ♦ Maximum performance is obtained at the resonance frequency.

- Ultrasonic motors are emerging new technology in consumer products (camera, etc.).
- No space qualified ultrasonic motor.

Comparison of existing electromagnetic (EM) and ultrasonic (US) motors

#	Type	Description	Manuf.	Stall Torque (in. oz)	No-load Speed (rpm)	Mass (g)	Torque Density - without gear (Nm/kg)
1	EM	DC, Brushless	Aeroflex	1.4	4.0K	256	0.04
2	EM	DC Brush	Maxon	1.8	6.0K	38	0.45
3	EM	AC, 3-phase	Astro	10.7	11.5K	340	0.21
4	us	Traveling wave - Disc	Panasonic	11.0	0.8K	70	1.10
5	us	Stand. Wave - Rod Torsion	Kumada	189.0	0.12K	150	8.80
6	us	Traveling wave - Disc	Shinsei	13.0	0.3K	33	2.70
7	us	Traveling wave -Ring	Canon	17.0	0.08K	45	2.30

ADVANTAGES OF ULTRASONIC MOTORS

Ultrasonic motors offer superior alternative to conventional motors.

- Without gear, average of 10 times higher torque density
- Simpler construction
- Not affected by magnetic field or radiation
- Self-holding force
- Low speed operation allowing direct drive
- Motor is compact with a pancake shape and easy to miniaturize
- Can be designed annular for electronic packaging
- Lower cost

SPACE QUALIFICATION OF ULTRASONIC MOTORS

AREAS OF CONCERN

- Operation temperature of commercial motors is specified for> - 10°C.
- Operation in vacuum can involve corona discharge and vacuum welding.
- Torque capability of reported motors is below 16 lb-in.
- Interface wear causes life time limitation (average operation of 1 K to 2K hrs).

THEORETICAL MODELING

To ***a priori*** predict rotary ultrasonic motors the transient and steady state performance an analytical model was developed and a summary will be given herein. The model consists of four sections as illustrated in Figure 1 and is described below. The model sections address the major components that are responsible for the motor operation, i.e. stator, rotor, interface and motor performance. .In Figure 3 the analytical model is drawn in the form of a flowchart with the four sections. The Stator Model (Section A) is a dynamic model of a circularly symmetric variable cross section disk. The disk is subject to distributed piezoelectric forces as well as distributed normal and tangential frictional interface pressures caused by motion dependent rotor-stator contact. The model includes traveling wave motion through temporally and spatially out-of-phase forcing of 90° orthogonal disk modes.

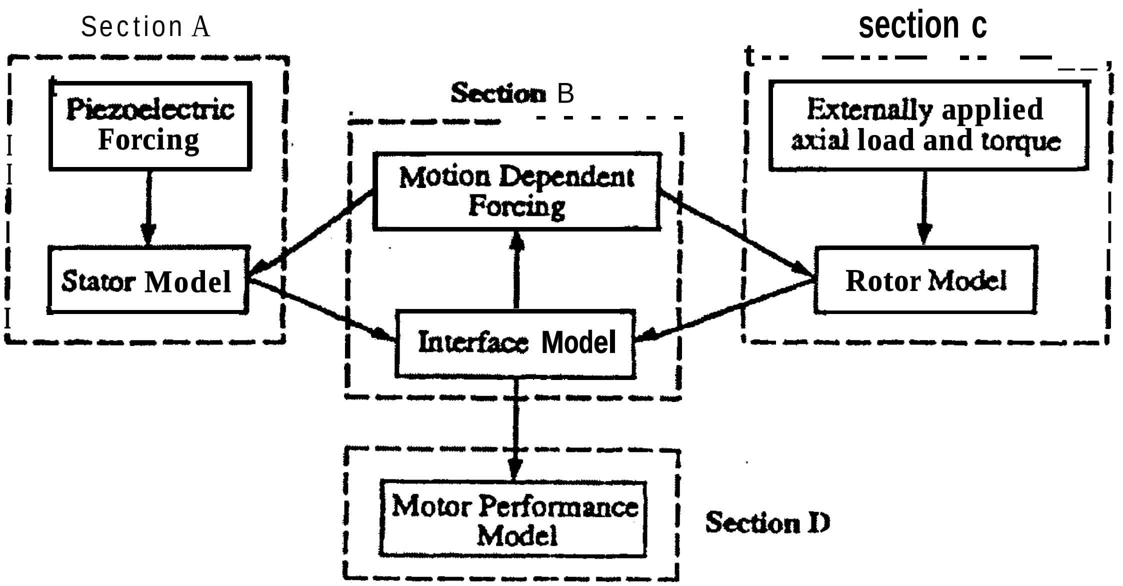


Figure 1: Modeling approach consists of major motor components which are: stator, rotor, interface, and motor performance.

In the Interface Model (Section B), a distributed frictional interface is assumed for the contact area between the rotor and stator. This provides for modeling the rotor-. stator contact compliance and allows distributed normal and tangential forces at the contact surface. The Rotor Model (Section C) assumes a rigid body dynamic model of the rotor motion (vertical and horizontal/rotary). It assumes an externally applied normal force and torque as well as motion-dependent interface forces that are derived from rotor-stator contact. The Motor Performance Model (Section D) provides a performance prediction module using transient or steady state values of rotor position and velocity to calculate positioning accuracy and steady state mechanical power output. It calculates the current input into piezoelectric electrodes using a filly coupled electromechanical model. Using the current and the known applied voltage it calculates average electrical power input and efficiency.

The piezoelectric constitutive equation in the model used can be expressed as

$$\begin{bmatrix} \boldsymbol{D} \\ \boldsymbol{T} \end{bmatrix} = \begin{bmatrix} \epsilon^T & e \\ -e^T & c^E \end{bmatrix} \begin{bmatrix} \boldsymbol{E} \\ \boldsymbol{S} \end{bmatrix}$$

where ***T* is** the stress tensor in reduced form, ***D*** is the electric displacement vector, S is the strain tensor in reduced form, and ***E* is the** electric field vector. The definitions of the stiffness constants c^E, the electromechanical constants e, and the dielectric perm ittivity constant ϵ can be found in [1 7]. The governing equation for the rotor can be written as

$$M\ddot{p} + C\dot{p} + Kp = \theta V + F_N + F_T$$

where ***M***, C and ***K*** are the mass, damping and stiffness matrices of the stator, respectively, and ***p* is the** model amplitude vector. F_N and F_T are the external normal and tangential force vectors, θ is the electromechanical coupling constants and ***V*** is the applied voltage.

The rotor is modeled by equations of motions decoupled in the rotary direction by the rotation angle α and in the z direction by the flexture height w_f (the distance between the undeformed stator height and the rotor lower surface). Hence, the rotation equation can be expressed as

$$I_{rotor}\ddot{\alpha} + C_{\alpha}\dot{\alpha} = \tau_{int} - \tau_{applied}$$

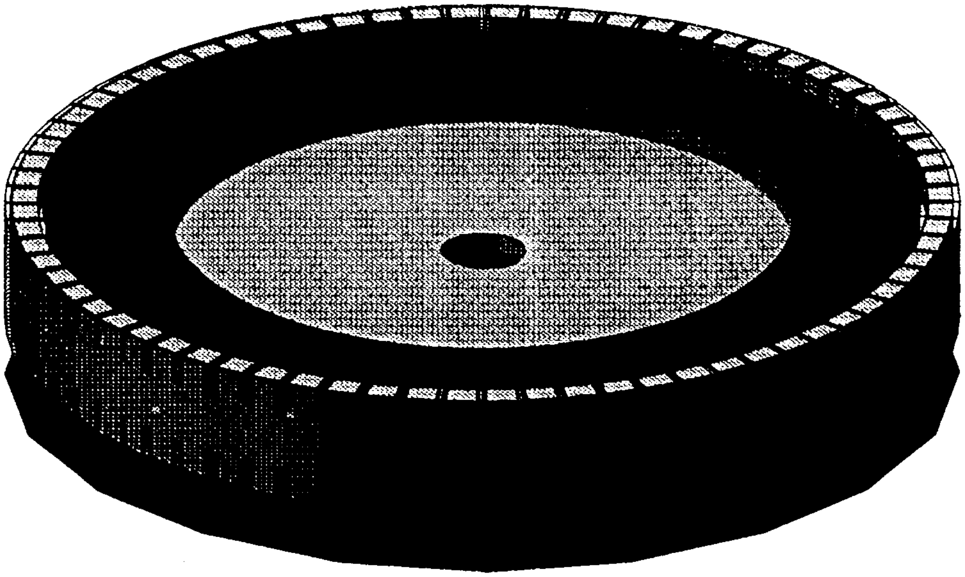
where I_{rotor} is the rotor inertia, C_α is the rotor spin damping, and τ_{int} and $\tau_{applied}$ is the interface torque and applied torque respectively. The equation of the rotor in the z direction can be expressed as

$$M_{rotor}\ddot{w}_f C_z\dot{w}_f = F_{int} - F_N$$

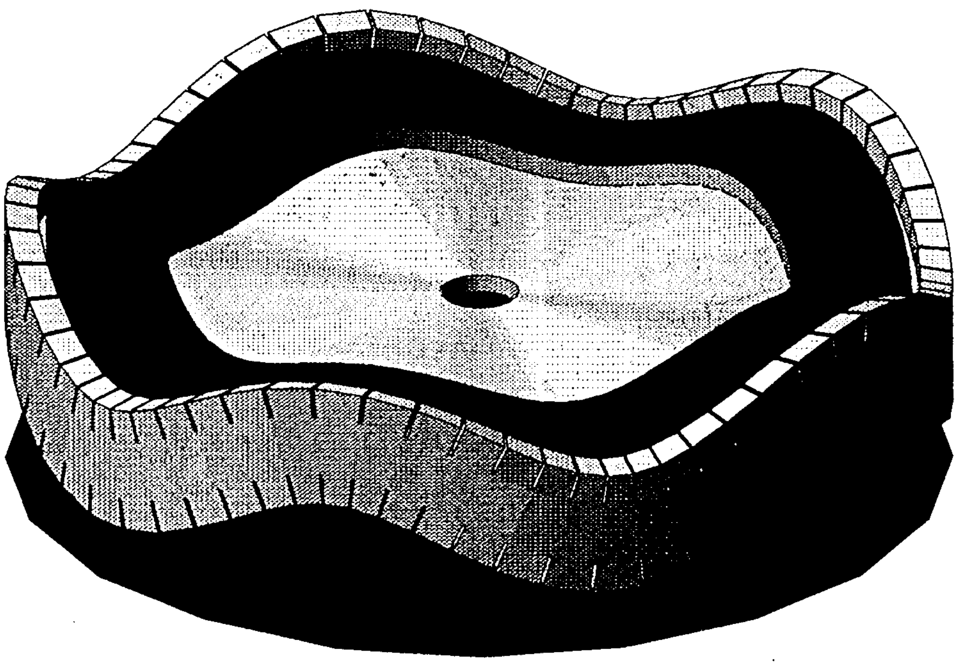
where M_{rotor} is the rotor mass, C_z is the rotor vertical damping, F_{int} and $F_{applied}$ are the interface force and applied forces, respectively. By solving the rotor and stator equations, the performance of the motor can thus be evaluated,

Piezoelectric Motor - Stator Model

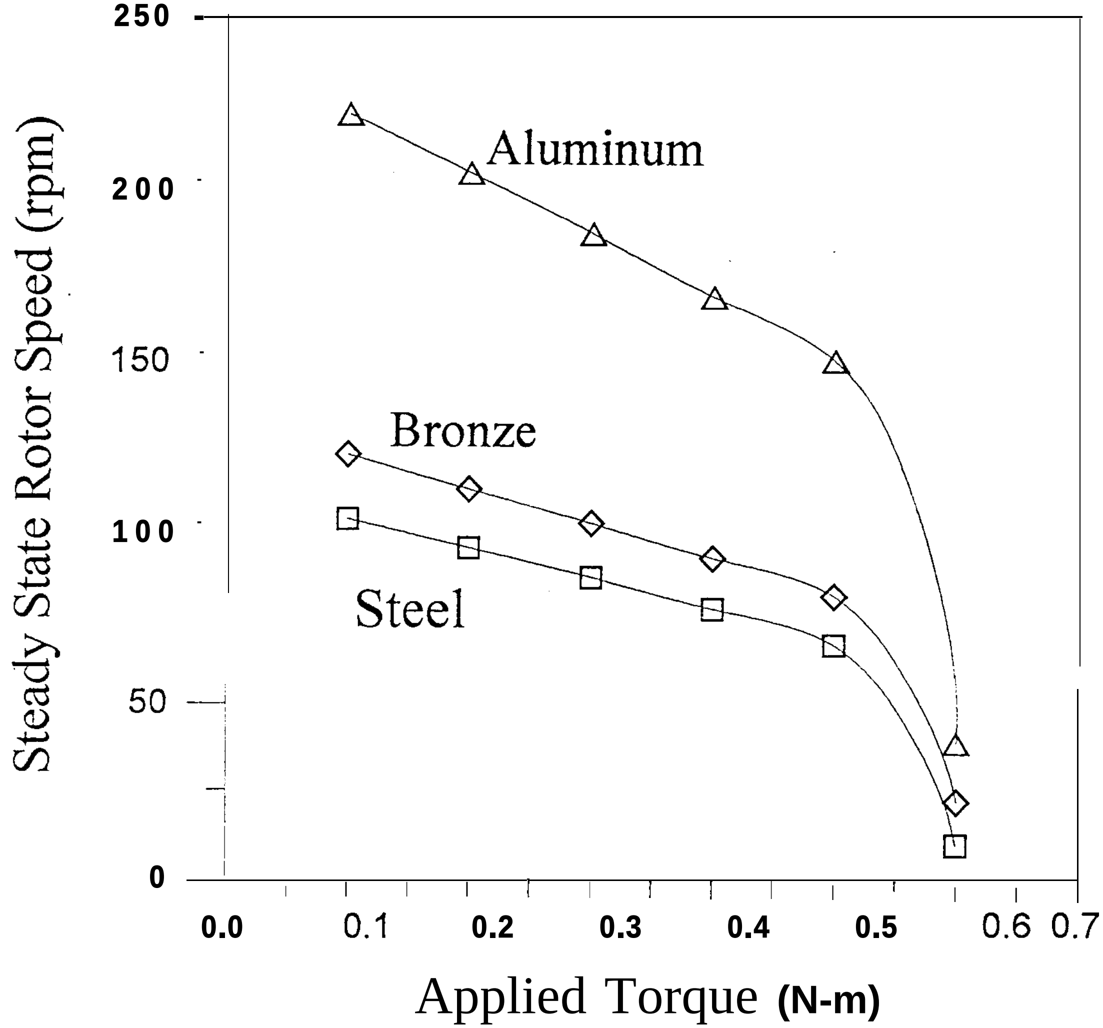
a. Stationary



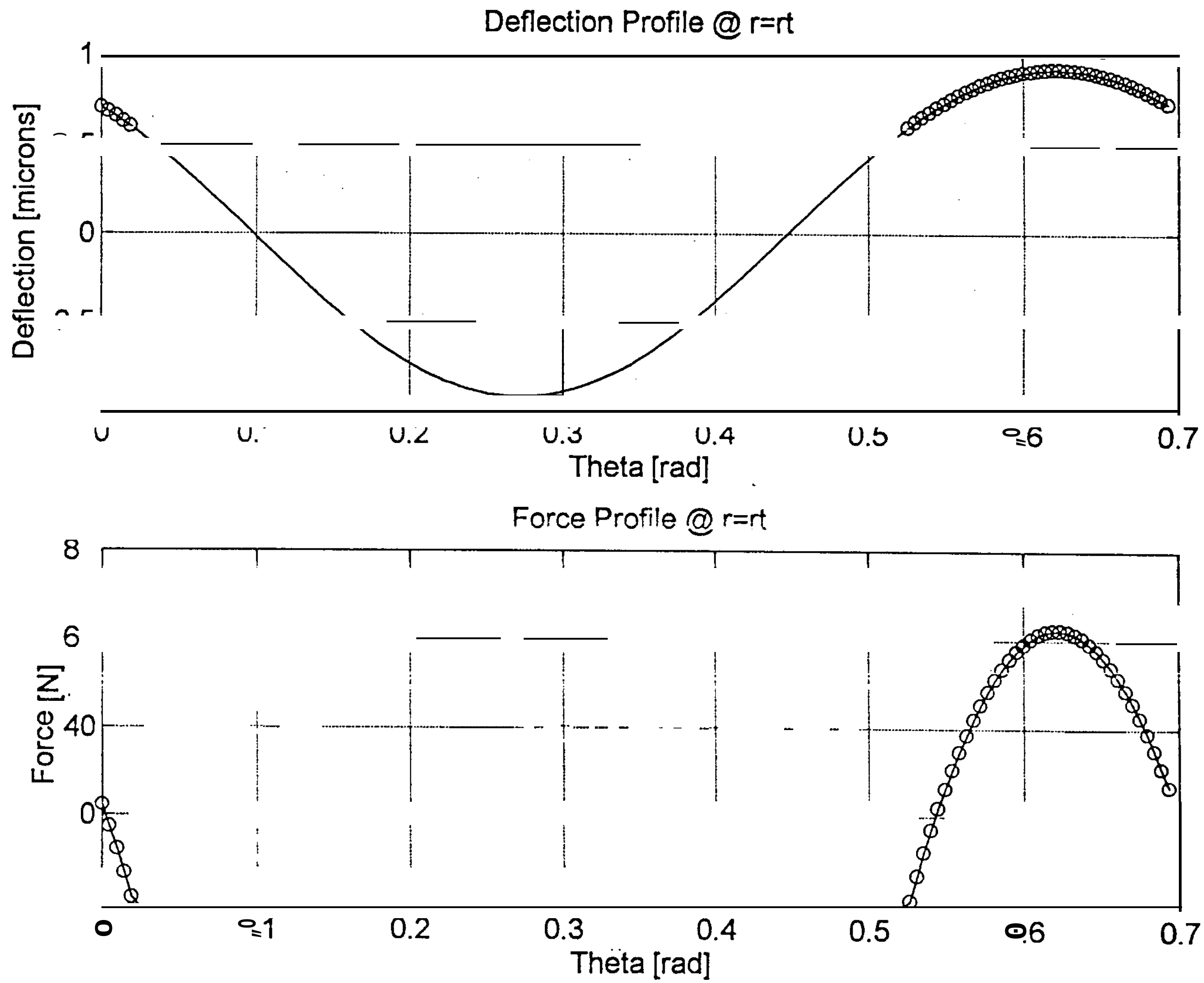
b. At arbitrary actuation position



MOTOR PERFORMANCE CURVES
FOR VARIOUS STATOR MATERIALS



DEFLECTION AND NORMAL FORCE AT THE RADIAL CENTER OF THE STATOR'S TEETH (CIRCLES INDICATE CONTACT REGION)



CONCLUSIONS

A parametric study of the motor model that account for the effect of the friction at the stator-rotor interface provided a valuable insight into the mechanical and dynamics of how piezoelectric motors operates. The model presented can be used to optimize the operation of piezoelectric motors including the effect of the teeth and the applied axial loading for maximum performance.